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Present State of Tevatron Lower Temperature Operation

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Present State Of Tevatron Lower Temperature Operation

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Fermilab continues to work on raising the particle energy of the Tevatron by lowering magnet temperatures using cold vapor compressors. In 1995, another two rounds of power tests were completed. These power tests, although showing significant improvement over the initial tests of 1993-94, have led to the conclusion that 1000 GeV operation cannot be attained without replacing/rearranging magnets with lower quench currents before the next Collider Run in 1999. Development of more cold compressor control strategies also continues.

INTRODUCTION

Since the installation of an upgraded Tevatron Cryogenic System in the summer and fall months of 1993 [1], engineers at Fermilab have been working on achieving reliable 1000 GeV (4444 amp) operation of the Tevatron accelerator in Colliding Beam mode. From December 1993 until late February 1996, during a 900 GeV physics run, engineers spent dedicated periods of time on two items: 1) power testing the magnets at lower temperatures in an effort to attain reliable 1000 GeV operation and 2) determining how to make cold compressor operations in the Tevatron reliable.

The results have led to the creation of better control algorithms for cold compressor pumpdowns and cold compressor reaction to system disturbances such as a quench. Further, we have concluded that to achieve 1000 GeV operation in our next Collider Run (1999) we must: remove known "limiting" magnets from our lattice, continue power testing after replacement, and optimize our temperature profile in each house.

REVIEW OF LOWER TEMPERATURE POWER TESTING

Since December of 1993, there have been three lower temperature ringwide power testing study periods. The initial test period [2] resulted in a steady state Colliding Beam energy of 975 GeV, operating at a cold compressor inlet condition of 3.93K (75.82 kPa). During this test period the Tevatron was also powered in a "ramp-to-quench" mode over a two day period. In this mode the magnets trained (nine training quenches total) and then peaked at 997 GeV. Scheduled power testing was concluded and the physics program began at 900 GeV.

In July 1995 a second power test period took place. Again the Tevatron was tuned for a uniform cold compressor inlet temperature of 3.93K at each satellite. Several changes were made in our methods for cold compressor operation and powering. First, when pumping down each of the systems, the helium flow was kept constant for each string by lowering magnet JT valve settings as we lowered two-phase pressure. In the previous tests we had not adjusted these valve settings and thus flow rates were considerably higher (see "New Controls Strategies"). Second, instead of ramp-to-quench power testing, the energy of the machine was raised in increments of 5 GeV after successfully ramping three times. This second round of tests resulted in six meaningful quenches (twice we had heater firing unit failures resulting in quenches). This time the peak quench energy was 990 GeV.

After a two month shutdown period for maintenance, a third round of power testing occurred in October, 1995. This time our results were very encouraging. We began by tuning the Tevatron to a uniform 3.93K temperature while also using the constant mass flow techniques previously discussed. It was at this time that we began to see the same set of cells quench repeatedly. The first two quenches occurred at magnet cells E24 and C42. These cells had also quenched in the July tests. This pointed to these magnets as being limiting elements. When a house contained a cell that repeatedly quenched, we adopted a strategy of lowering it's temperature to eliminate it from quenching. This allowed us to find the next limiting magnet cell.

The combined results of the July 1995 and October 1995 tests are shown in Table 1 and in Figure 1. In this third round of tests the machine successfully reached a quench energy of 1010 GeV. Although considered quite an achievement, it must be noted our goal is to attain a quench energy level of 1030 GeV to guarantee reliable 1000 GeV operation. In total we tuned 11 of the 24 houses to temperatures lower than the initial 3.93K. Fig. 2 shows the temperature profile we used in the final 1010 GeV quench.

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Table 1 1995 Power Test Quench Data

Quench Number	Date	Time	Quenching Cell	Quench Energy (GeV)	Quench Current (Amps)	Cold Compressor Inlet Conditions at Quenching House: 2φ Press (kPa)	Cold Compressor Inlet Conditions at Quenching House: 2φ Temp (K)	Comment
0				930	4129	127.5	4.476	
1	Jul 27	13:03	B32U	961	4267	75.81	3.928	on ramp up, very slow quench
2	Jul 27	16:08	E22U	980	4355	75.81	3.928	at flattop of 3rd ramp
3	Jul 27	20:01	F42U	Heater Firing Unit Problem. Data Invalid.				
4	Jul 27	22:55	C42L	990	4390	75.81	3.928	10 sec into flattop
5	Jul 28	00:44	F42U	Heater Firing Unit Problem. Data Invalid.				
6	Jul 28	02:37	C42L	990	4390	75.81	3.928	10 sec into flattop
7	Jul 28	09:00	C42L	990	4390	75.81	3.928	10 sec into flattop
8	Jul 28	12:13	E24U	990	4390	75.81	3.928	20 sec into flattop
9	Oct 12	18:38	E24U	980	4355	75.81	3.928	20 sec into flattop
10	Oct 12	21:42	C42L	985	4373	75.81	3.928	22 sec into flattop
11	Oct 13	03:49	C15L	992	4404	75.81	3.928	on ramp up to 995 GeV flattop
12	Oct 13	09:16	D19U	995	4418	75.81	3.928	on ramp uo to 1000 GeV flattop
13	Oct 13	15:36	D28L	1000	4440	75.81	3.928	10 sec into flattop
14	Oct 13	18:25	B19U	1000	4440	75.81	3.928	end of flattop
15	Oct 13	21:26	E24U	1005	4462	55.13	3.635	10 sec into flattop
16	Oct 14	05:03	C32L	1003	4455	75.81	3.928	on rampup to 1005 GeV flattop
17	Oct 14	10:59	D28L	1010	4484	68.92	3.837	12 sec into flattop
18	Oct 14	13:56	C48U	1000	4440	62.03	3.740.	5 sec into flattop of 3rd ramp
19	Oct 14	21:26	E24U	1010	4480	48.25	3.521	12 sec into flattop
20	Oct 15	03:54	B19U	1010	4484	68.92	3.837	end of flattop

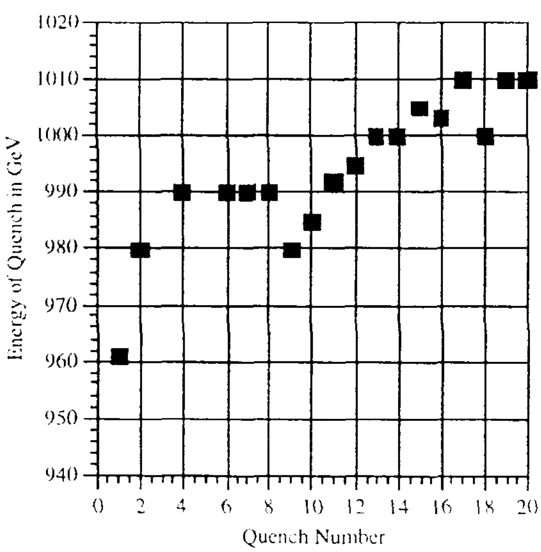

Figure 1 Quench Results of July - October 1995 Power Tests

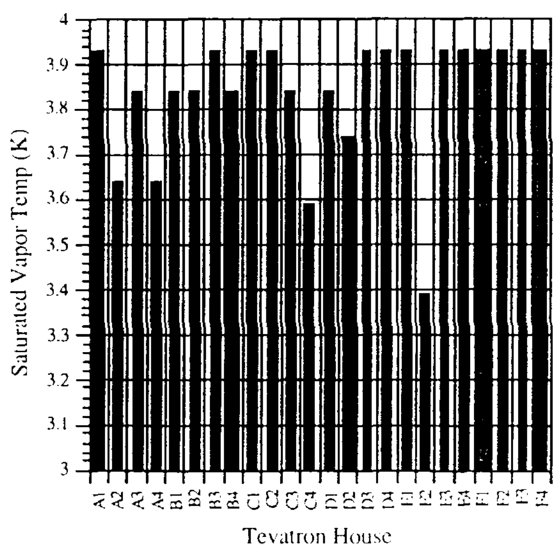

Figure 2 Tevatron Temperatuare Profile on the Final 1010 GeV Quench

Understanding and optimizing the temperature at each refrigerator is of vital importance as we are capacity limited at the Central Helium Liquefier (CHL). As discussed previously [3], the CHL provides liquid helium to each satellite refrigerator to boost its capacity. The amount of liquid helium required at each building is a function of the two-phase pressure and the speed of the cold compressor. If we do not optimize our temperature distribution at each refrigerator we risk needing more liquid helium than CHL can produce.

Before the conclusion of our tests, we purposely raised the temperature of a few select houses in an effort to identify, specifically, the magnet in each house that was causing the quench. This effort led to the identification of five magnets that will have to be replaced before we can expect to go to higher energies.

PLAN FOR ACHIEVING 1000 GeV OPERATION

The next Colliding Beam Physics Run, scheduled for 1999, is to be at a beam energy of 1000 GeV. In order to meet the goal of 1030 quench energy, a general plan has been developed and is presented here.

Magnet Replacement & Relocation

- The 1995 power testing identified five limiting magnets. During a two month shutdown in the Spring of 1996 we replaced two of these. While doing so we also identified and replaced two other magnets that are potentially limiting. The remaining three limiting magnets will be replaced during a future maintenance period.
- Using known Magnet Test Facility (MTF) test data we will continue to identify magnets in each of the 24 houses that we may want to remove or relocate (see Tevatron Configuration Analysis below). Removing or relocating these limiting magnets can only be done when problems arise in the Tevatron that necessitate warming up a house to 300K.

Magnet Test Facility Testing

- Test the thermal performance of the single phase and two phase circuits of a dipole magnet. One dipole has been highly instrumented and testing is on-going.
- Retest the removed "limiting" magnets from the Tevatron.

More Tevatron Power Testing

- Power test in May 1996 after a two month shutdown to understand the issue of re-training. During this shutdown 21 houses were at 80K and three houses were at 300K.
- Continue power testing as in 1995. Testing will start at 3.93K uniformly. Houses will be decreased in temperature as they quench. While power testing, we will identify the next set of limiting magnets.

Tevatron Configuration Analysis

Engineers are developing a precise Thermal Simulator for the Tevatron magnet strings. This simulator takes a much closer look at the thermal characteristics of dipole, quads, and specialty pieces than the normal instrumentation used to operate the machine. This simulation and old MTF quench analysis data are being used in combination to develop a magnet reshuffling program. A limiting magnet may not have to be removed from a house but merely relocated. This work has already been used in identifying potentially limiting magnets in a warm house (see Magnet Replacement and Relocation above).

NEW CONTROLS STRATEGIES

A new distributed control system was designed and installed as part of the Low Temperature Upgrade in 1993 [4,5]. The increase in complexity of each refrigerator required more sophisticated hardware and software capabilities than the original system, installed in the early 1980's. Our approach to the new system was to develop it in two phases. During Phase 1 our plan was to design and install the system to make daily operations reliable and equivalent to where we were with the original system. Phase 2 addressed issues like software to handle the impact of 24 cold compressors operating in the Tevatron. To date, we have accumulated 130,249 hours (average of 5427 per cold compressor) since the initial installation. This includes operating hours in powered and non-powered times. During this time we have slowly developed software to assist cold compressor operations reliability.

From years of experience operating the satellites, we know it is vitally important to develop very accurate and precise automatic programs for our major transient conditions. In the past this has included 300K to 4.5K cooldown and recovery from quenches. Our limited cold compressor experiences have made it obvious to us that automatic pumpdown to lower temperatures is even more crucial.

Using our Finite State Machine (FSM) software, a cryogenic engineer developed an algorithm that turns on the cold compressor and marches the machine up in speed in a controlled manner until the final pressure point is reached. As this is done, magnet string JT valves are tuned back to maintain a constant mass flow in the string while the refrigerator's dewar liquid level is adequately held within a margin. If liquid is boiled off too quickly, the program pauses, waits for dewar level to be within proper tolerances, and pumpdown resumes. Total pumpdown from 4.6K to 3.9K at the inlet of the cold compressor takes approximately 45 minutes and another 10-15 minutes to reach equilibrium at the far end of the magnet strings [6] (see Fig. 3).

In the future each refrigerator could operate at a different two-phase pressure point with different JT valve settings. It is important to have an easy method for remembering such items as JT valve settings with cold compressors on or off and final cold compressor inlet pressures. We have developed a MicroVAX application program that resides on the control network containing this ringwide information. An operator, before starting a pumpdown of a house, can automatically download this table to that house. The list is used by the FSM described above. As critical parameters change they can be edited within the MicroVAX application. Multiple files are made possible if needed. An important note is that JT valve settings need to be adjusted back to the 4.5K tune if, for any reason, the cold compressor is turned off.

We have spent many hours studying cold compressor behavior during Tevatron quench events. All 24 refrigerators have common supply pressure and return pressure piping. As a result, whenever a quench of a magnet occurs, every refrigerator sees a highly elevated suction pressure. This has led to trips of the cold compressors. The scenario is as follows: 1) a quench occurs, 2) suction side pressure elevates rapidly which translates into the compressor intake elevating, 3) a dedicated PID control loop tries to speed the machine up to pumpdown, 4) the machine takes a large step in speed and suddenly appears to stop pumping, and 5) finally the machine trips on very high current draw. We have taken two steps to eliminate this problem. First we have changed our PID loop to limit ourselves to 100 rpm changes per step (a step change is allowed every 6 seconds). Second, during a quench, magnet pressures peak in 250 msec. This means suction pressure will also rise very quickly. To avoid nuisance trips due to quenching we have found that we can lock the speed of each cold compressor until suction pressure returns to nominal values. We accomplish this by interfacing our refrigerator microprocessors to a Tevatron Clock Event system. This event system broadcasts a quench occurance. The refrigerator processors read this event and then disable PID loops from updating. Tests of this method have shown we can eliminate unnecessary trips due to quenches.

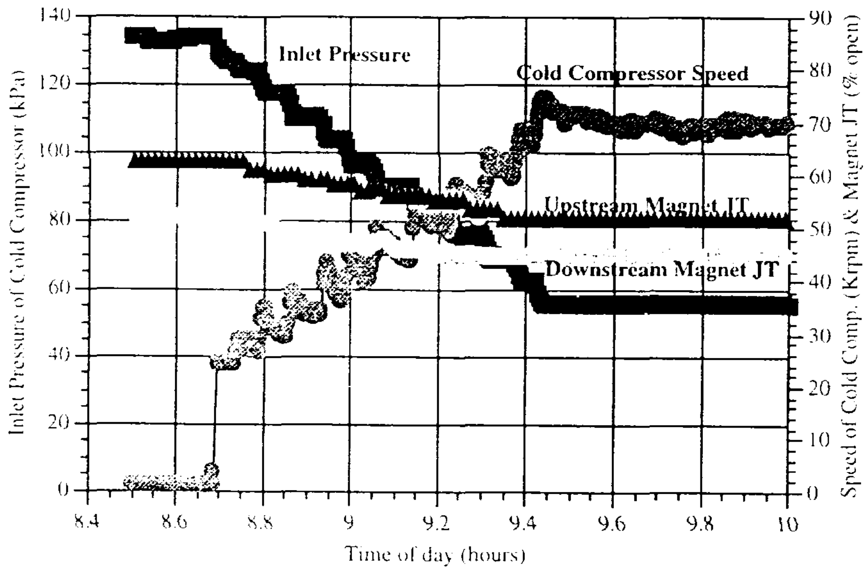

Figure 3 Automatic Cold Compressor Pumpdown with Magnet JT Tuning

CONCLUSION

Power Testing at lower temperature over the past year has surpassed the 1000 GeV energy barrier with our ultimate goal being 1030 GeV. Plans are to continue testing while identifying and replacing/relocating limiting magnets. We continue to gain experience with operating cold compressors in the Tevatron. With this experience specialized controls features are developed to address our needs. These efforts will continue so that we may operate reliably at higher energies beginning in 1999.

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